Chapter 14
Energy and Environmental Issues

As stated in Part II, two of the problems the automotive industry had to solve starting from the 1960s were related to the environmental impact due to the widespread use of road vehicles, in particular in highly populated areas like cities, and the use of energy, and in particular fossil fuels. Since then strict regulations have been imposed regarding emissions, while it was left to the market forces to take the task of convincing manufacturers to invest in reduction of fuel consumption. This trend was reinforced in the following years and the standards on emissions and then also on consumption, became increasingly strict.

At present, environmental regulations do not deal only with substances that can be defined as pollutants (unburned hydrocarbons, NO_x, CO, particulates, etc.), but also with greenhouse gases like carbon dioxide (CO_2). The latter cannot be considered as a pollutant, since it is in itself not dangerous for life-forms (it is essential to plant life), but above a certain global concentration may cause an increase of the temperature of Earth. Note that some greenhouse effect is required, since without it Earth would be too cold.

The two problems are here dealt with together, since some solutions that would reduce pollution could cause an increase of fuel consumption and vice-versa. For a correct approach, they should be studied in a global way: it is not just a problem of how much pollutants are produced or energy is used by a certain vehicle when it operates, but what is the global pollution and energy consumption of a given vehicle through its whole life-cycle, i.e. the pollution and energy requirements in a vehicle's production, maintenance and disposal must be also accounted for. Operating in this way the total distance travelled by a vehicle in its useful life becomes important: If a vehicle is little used what most matters is the pollution and energy consumption in construction and disposal, while the importance of these two phases of the vehicle lifecycle is reduced with increasing distance travelled by the vehicle during its life.

Any change in a vehicle that is introduced to reduce its emissions or to improve its fuel efficiency, but affects negatively the pollution or energy use in its construction (for instance owing to the greater complexity or the use of particular materials) has a positive effect starting only from a given actual utilization of the vehicle. For instance,

G. Genta et al., *The Motor Car*, Mechanical Engineering Series,
DOI: 10.1007/978-94-007-8552-6_14,

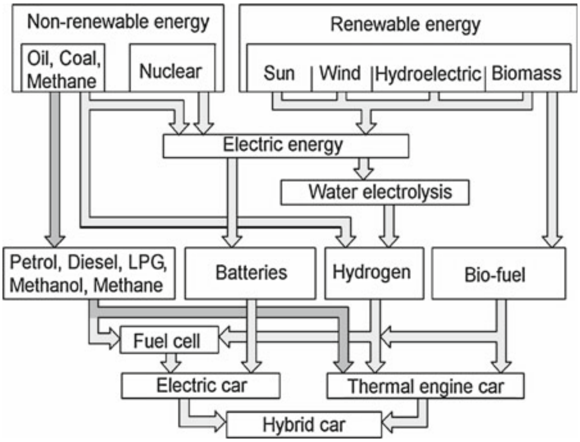

Fig. 14.1 This chart shows how primary energy sources, classified as renewable and non-renewable, can be conveyed to their final use. The darker path is the traditional one

a complex hybrid vehicle may be expedient if used as a taxi, but not as a private, seldom used, city car.

The ways proposed for improving future vehicles from these viewpoints are many, but the main ones are related with innovative drivelines: electric vehicles, hybrid vehicles, vehicles using 'alternative' fuels. This does not cover all the possible innovations in this sector, since any improvement that can be made in energy efficiency in general, like reducing aerodynamic drag, rolling resistance, weight, etc. causes a reduction of energy consumption and, as a consequence, reduces pollution owing to decrease of the fuel that has to be burned.

The energy needed for motor vehicle propulsion may be generated and stored in various ways. Traditionally, non-renewable sources of energy, mostly oil and derivate products (gasoline and diesel fuel) have assumed a dominating, although not exclusive, role. Technological developments today allow us to design different scenarios in which primary renewable sources of energy may come into play, contributing to both improving environmental conditions and safeguarding the reserves of natural resources which may no longer be available in the future.

The chart in Fig. 14.1 shows the primary energy sources that can be used by each kind of propulsion system and how they are conveyed to their final use. The intermediate forms of energy can also be called *energy vectors*. The chart is far from being complete, but it covers the traditional approach (darker path) and many of those that have been suggested for the future. In particular, hydrogen has been assumed to be produced through water electrolysis, while at present only 3 % of the total hydrogen production is treated in this way.

A vehicle fleet including vehicles propelled by internal combustion engines (gasoline, diesel, LPG, natural gas and hydrogen), electric batteries, hybrid systems and fuel cells can have its energy requirements met by diversifying the sources of energy

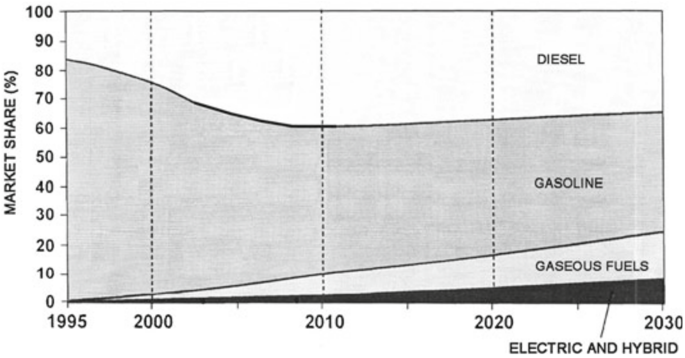

Fig. 14.2 Possible scenario for market shares of present and future fuels/power plants

including renewable, and therefore inexhaustible, ones. Even internal combustion engine fuels may be derived from oil, coal, natural gas (methane), biomass decomposition or water hydrolysis (hydrogen). On the other hand, the electricity needed to fuel electric and hybrid vehicles and to produce hydrogen through water electrolysis may be generated by thermal, nuclear, hydroelectric, wind or solar power stations.

In conclusion, today's exclusive dependency on oil and derivate products could be mitigated by diversifying the type of vehicles in the fleet and therefore the sources of energy needed to meet demand. In this light, to ensure sustainable mobility whilst protecting the environment and saving energy, the motor vehicle fleet will gradually evolve by adopting a diversity of power plant solutions. A prediction of the possible future development of car power plants in Europe in the next 20 years is shown in Fig. 14.2.

In this prediction, gasoline and diesel engines will continue to dominate the market in the foreseeable future. The introduction of direct injection and current progress in engine management strategies and exhaust gas post-treatment systems will ensure that the ambitious emission and fuel consumption targets stated by new emission and consumption standards are met without sacrificing the flexibility, convenience and driving pleasure we are used to enjoy. Concurrently, the market share of gaseous fuels powered engines—LPG and especially natural gas—is expected to continue to increase as in general, motorists consider their performance to be comparable to that of conventional engines, are cheaper to run (provided the current level of fuel taxation is maintained) and are more environmentally friendly.

Electric cars, despite their limited range and high costs (bound to remain so for many years to come) may offer the right solution for urban mobility, if made available at city entry points where motorists can park their own vehicle and hire an electric car for use in town. Initiatives of this kind, tried in European cities, are proof of the feasibility of such solutions. Fleets of vehicles owned by public authorities and private companies may also be converted to battery electric vehicles without losing in efficiency and with significant advantages for the urban environment.

Table 14.1 From electrochemical energy density *ED* to battery energy density, in batteries considered for electic vehicals

Battery type	Electrochemical ED (Wh/kg)	Cell ED (Wh/kg)	Battery ED (Wh/kg)
Lead–Acid	170	40	30
Ni–MH	180	70	60
Li–ion	710	150	120

Finally, whilst hybrid or fuel cell powered cars can offer near-zero emissions and solve the problem of limited range of electric cars, their impact is unlikely to radically alter the future scenario, because of their cost; nevertheless they represent the only available technology to reduce consumption and emissions to a minimum, without changes in our everyday life. A prudential estimate suggests that the total of electric and hybrid vehicles is expected to reach a 10 % share of the market.

14.1 Battery Electric Vehicles

At the end of Part II it was said that the main problems that today hamper the diffusion of battery electric vehicles are still the same problems that caused them to be abandoned in the past. The situation will be mitigated in the future, thanks to the introduction of new and better batteries, but the improvements in this area can only be pushed up to a point. The available space for improvement can be estimated from Table 14.1, in which the maximum theoretical energy density of some battery systems is compared with the energy density actually achieved at a cell and a battery level: It is clear that the theoretical energy density, that takes into account only the mass of the electrochemical reactants, is a maximum that cannot be closely approached. Some space for improvement is shown also by the comparison of the cell energy density with the actual battery energy density; some savings in the mass of the battery structure integrating cells, installation interfaces and cooling system that are usually needed can improve the energy density of all battery types.

However, the problems related with battery electric vehicles are more linked with their mass production in large quantities than with designing and building vehicles of this type that can satisfy the customers' needs. The first point, as already discussed, is the large scale availability of the materials needed to build the batteries, like lead or lithium.

Even worse problems are related to the energy requirements. The energy consumption of a battery electric vehicle is not better than that of a conventional vehicle, but it is likely worse. Electric energy has to be produced in power stations from the primary source, then transported along the electric lines, used to charge the vehicle battery and then transformed into mechanical energy in the electric motor. Each step has its own efficiency, in particular the charging and discharging of the battery has

an efficiency that depends on many factors, but cannot be very high. The average efficiency with which electric energy is produced at the power station is much higher than the efficiency of the internal combustion engines of cars (typically 39 % against and average of 20–25 %) but this is usually not enough to compensate for the larger number of energy transformations from the primary source to the wheels.

Battery electric vehicles have the energy advantage of allowing regenerative braking, a thing that improves their energy efficiency, but also the disadvantage of not allowing the use of waste heat produced on board for heating. Particularly in cold weather, the heating of the passenger compartment must be made by tapping energy from the batteries or burning a small quantity of fuel. While in the second case the efficiency is quite good, but the implementation is tricky and an on-board tank for the heating fuel is required, in the first case the efficiency is low, since the efficiencies of the chain starting from the power station and ending at the battery must be accounted for. Slightly better is the alternative of storing thermal energy on board, since at least the losses linked with the charge and discharge of the batteries are avoided, but an additional thermal energy storage system must be introduced, and the efficiency of the thermal insulation of the passenger compartment must be improved over present standards. For air conditioning there is little to say: energy must come from the battery, decreasing the range and increasing energy consumption.

Similar considerations hold for pollution and greenhouse gas emissions. Electric vehicles are considered to be Zero Emission Vehicles (ZEV) , but actually, as already said, they have the advantage of moving the pollution from the place of use of the vehicle to the place where the electric energy is generated. This may be a good advantage in avoiding pollution in congested urban areas, but has no global effect, except for the better pollution control that can be achieved at the power station.

The result for both energy and environmental issues depends strictly on the mix of primary sources used in any particular country. If the electric power is generated mostly using oil-based fuels, the energy advantages are at best irrelevant and usually counter productive, as is the impact on greenhouse gas production. The well-to wheel energy consumption is bound to increase with a large use of electric vehicles. If large use is made of coal, the greenhouse gas production is worsened. Only if the primary source is nuclear, or for the small percentage they can contribute to, renewable sources, there is an advantage in a large use of electric vehicles, that are a solution suited only to an energy-rich society, possibly based on nuclear power.

Note that all the above considerations are in a way incorrect, because they do not take into account the whole life-cycle balance, and specifically do not take into account the energy required to build the batteries (that have a limited life), and the energy and costs related with the required increase of generation capacity and with the increase of the capacity of electric power lines, even if the last two can be mitigated by charging the batteries in off-peak hours.

Other improvements, that in the last years made the construction of effective electric cars possible, are linked with advancements in electric motors and power electronics technology. Brushless, rare earths, permanent magnet motors, can reduce the bulk and weight of the powerplant as well as increasing their efficiency, even if

the average efficiency of the small electric motors used on cars is quite lower than that often quoted figure of 90 %.

Here another limitation can be predicted: the availability of neodymium, essential in the production of powerful neodymium–iron–boron magnets for electric motors and generators, is limited and its production is at present less than 20,000 tons per year. A severe shortage of neodymium, whose production is concentrated (about 97 %) in a single country (China) and the subsequent sharp price increase, is predicted for the foreseeable future. For sure, the neodymium reserves are insufficient to build a number of electric motors corresponding to the conversion of a large portion of vehicles to electric power.

As a conclusion, battery electric vehicles are improving their performance, and there is no doubt that prototypes with performance similar to those of conventional vehicles can be built already at present and, even more, in the near future. To build a good number of such vehicles at a cost and with an ease of use matching what the customers at present expect from a car is a more difficult task, although a task manageable in the future. What at present seems to be unfeasible, and even inadvisable, is an attempt to substitute altogether present internal combustion vehicles with electric vehicles.

Even worse are the perspectives for electric vehicles powered through fuel cells; some experts believe that fuel cell cars will never become economically competitive with other technologies or that it will take decades for them to become profitable. In July 2011, the Chairman and CEO of General Motors, Daniel Akerson, stated that while the cost of hydrogen fuel cell cars is decreasing, "The car is still too expensive and probably won't be practical until the 2020-plus period, I don't know."[1] Similarly, Steven Chu, the US Secretary of Energy of the Obama administration, stated that hydrogen vehicles "will not be practical over the next 10–20 years."[2] Furthermore, he stated that since hydrogen is primarily obtained by reforming natural gas, some of the energy content of natural gas is lost and there does not yet exist a good storage mechanism for transportation.

Fuel cell technology thus seems to be a hypothetical alternative for the far future, in a scenario of abundant energy produced by a primary source different from fossil fuels and after the problems related with production, storage and distribution of hydrogen (see below) have been solved.

14.2 Hybrid Vehicles

Hybrid vehicles provided with an internal combustion engine, one or more electric motors and an electrochemical battery are already on the road and were described when dealing with the present state of the art.

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[1] Shepardson, David. *"GM CEO: Fuel cell vehicles not yet practical*". The Detroit News, July 30, 2011.

[2] Chu, Steven. *Winning the Future with a Responsible Budget*. U.S. Dept. of Energy, February 11, 2011.

The question whether they represent the future of automotive vehicles is often asked. There is little doubt that:

- They require smaller batteries and (in some configurations) smaller electric motors than battery electric vehicles. The difficulties linked with large scale production and to the limited supply of battery materials (lead or lithium) and motor material (neodymium) are thus less severe;
- they are more energy efficient than both conventional internal combustion engine vehicles and battery electric vehicles;
- their emissions are less harmful that those of conventional vehicles. Although they pollute more than electric vehicles in the place of utilization, the comparison in terms of global pollution and the production of greenhouse gases depends on the mix of primary energy sources with which the batteries of the latter are charged.
- they are free of some of the typical drawback of battery electric vehicles, like limited range, recharge time, increase of electric energy consumption and increase of the electric energy transportation capability.

On the other side, they are surely more complex than both conventional and battery electric vehicles and the energy required for their construction is likely to be larger than that required for at least conventional vehicles.

An assessment on this issue is made more difficult by the wide variety of hybrid vehicles that are presently built and are proposed for the future: They go from what are practically battery electric vehicles with a small on board charging facility, to almost conventional vehicles with a device to recover braking energy and to improve acceleration. In this sense, racing cars with a Kinetic Energy Recovery Storage (KERS) could qualify as hybrid vehicles, even if usually this term is restricted to vehicles in which the amount of energy stored is larger.

The present and, even more, the future improvements in the battery field answered to the objection that batteries do not have the power density for applications of this kind, or at least that they work in inadequate condition on hybrid vehicles, causing a short life. To avoid this problem, mostly related to lead acid batteries, hybrid vehicles with supercapacitors, flywheels or compressed air storage were proposed in the past, either as simple hybrids (with, for instance, internal combustion engine and flywheel) or ternary hybrid (internal combustion engine, batteries and flywheel). The latter solution seemed to be optimal, because both energy storage devices work in optimal conditions, but their complexity is larger, perhaps impractically so.

Most of these problems were solved with advanced batteries, and lithium batteries lend themselves optimally to the use on hybrid vehicles, although with some safety problems.

The efficiency of the internal combustion engine is important, and thus a definite improvement is obtained by using a small diesel engine instead of a spark ignition engine. Attempts to use small gas turbines , on the basis of their higher efficiency, have been done (see below). Specifically designed engine-generator units are under study for series hybrid, in which the unit has no mechanical energy output. Configurations can be used in which the pistons operate linear generators directly, without needing to transform reciprocating into rotational motion.

In conclusion, while it is certain that hybrid vehicles are the best solution for many applications, such as vehicles used mostly in an urban environment and that travel a long distance during their life (taxis being a typical example), it is questionable whether vehicles which are used less, or operate mostly outside cities, could really benefit from hybrid technology. It is possible to predict that the improvements in battery, motor and power converter technologies will cause the number of hybrid vehicles to increase in the future but a complete substitution of conventional vehicles can be considered as unlikely.

14.3 Non-conventional Fuels

14.3.1 Hydrocarbons and Oxygenated Fuels

The large majority of motor vehicles at present use two types of fuel, both derived from oil: gasoline and diesel fuel. They are made by hydrocarbon molecules that are fairly big and complex. For instance, a typical molecule found in gasoline is isooctane, C_8H_{18}, and a typical molecule of diesel fuel is cetane, or n-hexadecane, $C_{16}H_{34}$. Since they contain a fairly large quantity of carbon, they produce a large quantity of carbon dioxide when burned.

The simplest hydrocarbon, and the one that produces the least carbon dioxide, is methane, CH_4, the primary constituent of liquefied or compressed natural gas. A slightly more complex one is propane, C_3H_8, the primary constituent of liquefied petroleum gas (LPG).

Non conventional fuels contain also constituents that are not strictly hydrocarbons, but contain also a small quantity of oxygen, like alcohol fuels such as methanol, CH_3OH and ethanol C_2H_5OH, and biodiesel. They are often referred to as oxygenated fuels.

The pollution produced by burning all these fuels depends mostly on how they are burned and how the exhaust gases are dealt with; it is thus more a matter of the engine than of the fuel: in ideal conditions the combustion products of all these fuels would be only carbon dioxide and water. On the contrary, the amount of carbon dioxide produced depends on the ratio between the ratios of the carbon and the hydrogen atoms the fuel contains. The specific CO_2 emission referred to the energy contained in the fuel is 0.25 kg/kWh for gasoline, 0.27 kg/kWh for diesel fuel, 0.23 kg/kWh for liquid petroleum gas and 0.20 kg/kWh for natural gas. These values depend however on the exact composition of the fuel and on the assumption made on how well the combustion is carried out. At any rate they refer to the energy contained in the fuel; to refer them to the energy produced by the engine the efficiency of the latter must be kept into account. This is important above all when comparing gasoline with diesel fuel, since diesel engines have a better efficiency than spark ignition ones.

The use of LPG or natural gas and above all methane (the hydrocarbon with least carbon) instead of gasoline or diesel would reduce CO_2 emission, although not by

a large proportion. They are also considered beneficial for pollutant emissions in general, since it is easier to keep low the contents of most pollutants, in particular unburned hydrocarbons and particulate.

A completely different issue is the use of biofuels, including alcohol produced from plants and biodiesel: They are usually considered to have a specific CO_2 emission equal to zero. The rationale behind this statement is that by producing the biological material from which the fuel is produced the plants subtract from the atmosphere the same quantity of carbon dioxide that will be reintroduced when burning the fuel, with a zero greenhouse gases balance. The problem with biofuels is not technological, but an economical and ethical one: if crops are specifically cultivated for producing fuels in any globally consistent amount, this will result in a reduction of the soil dedicated to growing edible plants and thus in a decrease of the food production and an increase of food price. A different matter is whether biofuels are produced from crop residues and waste (straw, cellulosic biomass, etc.). These considerations are controversial, with some asserting that the food price increase of 2007–2008 was due to the increase of biofuel production, and defining the latter as a crime against humanity, and others who stated that the impact of biofuel production on the price of food was small. At any rate the idea of using land to cultivate plants for the primary reason of producing fuel does not seem to be good.

As a general conclusion it can be stated that the use of alternative fuels does not require substantial changes as far as vehicles are concerned, since most engines can be easily adapted at the factory to burn different fuels. This is the reason why so many prototype vehicles burning a wide variety of alternative fuels were presented and demonstrated at shows. The problems mostly regard the distribution networks to make these fuels available to the general public and thus are of organizational and not of technical nature. In some countries, like Brazil, there is already a good experience in using biofuels (e.g. bioethanol) or various mixtures of traditional and alternative fuels (like the so called gasohol, 10 % ethanol and 90 % gasoline, or E85, 85 % ethanol and 15 % gasoline). In any case, the use of these fuels can improve the situation as far as greenhouse gases themselves are concerned, and can decrease the dependence of a country on imported energy products. From a global viewpoint, however, in countries where a good fraction of the electric energy is produced by fossil fuels, it is not of much importance whether biofuels are burned in cars or in power stations.

14.3.2 Hydrogen

14.3.2.1 Generation

Hydrogen was discovered by Cavendish in 1766 (Fig. 14.3). Lavoisier realized that it was an element, and named it hydrogen; immediately it was realized that it was very flammable and difficult to contain since it escaped from even the smallest porosities of the container. Nonetheless, just 17 years after it had been discovered, large

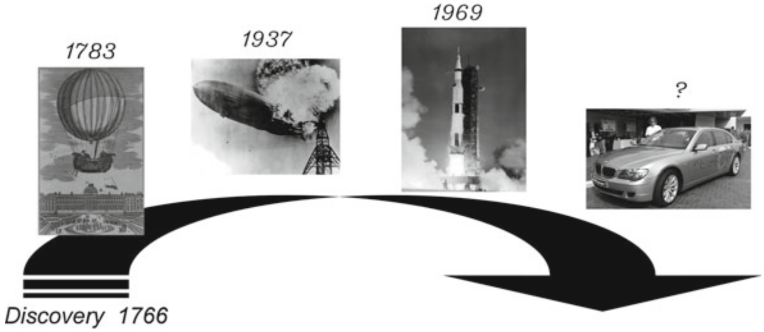

Fig. 14.3 Hydrogen: from its discovery by Cavendish to its possible future use as an energy vector for cars

quantities of the gas were used by Jacques Charles to inflate an aerostat which flew on December 1st, 1783. This was almost the only use of hydrogen for 200 years (apart from applications in chemical laboratories[3] or industry for the production of methanol, ammonia, etc.), until the Hindemburg disaster (1937) ended its use in lighter-than-air machines, which have been since then inflated by helium. Since the 1960s it became a widespread fuel for rocket engines, owing to the high specific impulse of the hydrogen-oxygen propellant combination.

When burning hydrogen no carbon dioxide is produced and so no contribution to the greenhouse effect can result. The exhaust is also much cleaner, with no unburned hydrocarbons, particulate and carbon monoxide. The only emissions can be related to NO_x.

In the automotive field hydrogen can be used in two different ways: burning it in a more or less conventional engine or using it in a fuel cell to produce directly electricity.

At any rate hydrogen is not an energy source: although being by far the most common substance in the universe, our planet does not contain any free hydrogen. We can say that all the hydrogen available on Earth is either 'already burnt' (water) or combined with a variety of other elements in many compounds. Energy is required to extract hydrogen, and this energy is then given back when it is recombined. Hydrogen is thus an energy accumulator, a sort of chemical battery.

The (conceptually) simplest way to produce hydrogen is by electrolyzing water, but this requires huge quantities of electric energy. An electrolytic cell plus a fuel cell forms what is usually called a reversible fuel cell, that is a sort of rechargeable battery, with a disadvantage that it requires intermediate storage of hydrogen, which is something not easy at all, as it will be seen later. Water can be decomposed also by heat, but the temperature at which it spontaneously dissociates is around 2,500 °C, too high for industrial applications of thermolysis. Catalysts can be used to reduce

[3] It should not be forgotten that also the very first internal combustion engines, such as the prototypes developed by Barsanti and Matteucci or by De Rivaz, ran on Hydrogen.

this temperature. The sulphur-iodine cycle is promising for producing hydrogen from water in high temperature nuclear reactors.

Actually just about 3 % of hydrogen is at present produced by electrolysis, while the remainder is obtained from chemical reactions involving a fossil fuel, like natural gas, carbon or oil. A common approach is steam reforming, in which steam reacts at high temperature (700–1100 °C) with methane:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \ .$$

The carbon monoxide reacts again with water at about 130 °C, yielding:

$$CO + H_2O \rightarrow CO_2 + H_2 \ .$$

This way of producing hydrogen has an energy efficiency of 80 %, so that when hydrogen is burned to produce energy, less energy is obtained than it would by burning methane directly. These reactions produce large quantities of carbon dioxide, and overall the quantity of greenhouse gases is larger when methane is transformed into hydrogen and burned than when it is burned directly (at equal thermal energy produced by the combustion). If the hydrogen is used in a fuel cell, and if the efficiency of the system made up of the latter plus the electric motor is higher than that of the thermal engine, then an improvement from this viewpoint may be obtained.

Other reactions of the same type can be used for different hydrocarbons, although all of them produce huge quantities of carbon dioxide. There are however reactions whose end product is not hydrogen and carbon dioxide, but hydrogen and carbon black: operating in this way however, less than half of the energy contained in the original hydrocarbons is at the end contained in hydrogen. A good quantity of energy ends up in the carbon, and cannot be extracted without producing CO_2.

Quite promising is the production of biohydrogen, i.e. the conversion of biomass and biological waste into biohydrogen through biomass gasification, steam reforming or biological conversion like biocatalysed electrolysis or fermentative hydrogen production. The latter involves the use of bacteria, through biolysis, photofermentation, dark fermentation, enzymatic hydrogen generation or biocatalysed electrolysis.

As a result, a widespread use of hydrogen in vehicles makes sense only if the primary source is different from fossil fuels: the true advantage of hydrogen is that it transforms into a portable energy source those sources that are not portable, such as nuclear energy, but also hydroelectric, solar, wind and other renewable sources. In particular, the use of processes that do not pass through electric energy allow production of hydrogen directly from nuclear energy, so allowing us to power vehicles from nuclear energy in an indirect way.

14.3.2.2 Storage

The same feature that makes hydrogen so well suited to aerostatic applications, namely its low density, is its main drawback in its applications as a fuel. When used

as a rocket propellant hydrogen is stored as a cryogenic liquid: its boiling temperature at atmospheric pressure is about 20 K, i.e. −253 °C. In these conditions its density is just 71 kg/m^3, i.e. 1/14 of the density of water. The size of the huge external tank of the space shuttle is due to this reason; if it contained a hydrocarbon like kerosene it would be about ten times smaller. Moreover, the liquid hydrogen tank must be filled a short time before launch, and any time spent between filling and utilization causes a severe boil-off of the fuel, with the ensuing waste and above all the risk of fire, owing to the high flammability of the mixture of hydrogen and air.

In automotive applications it is possible to use liquid hydrogen, but the tank must be a true insulated cryogenic tank, able to keep its content at a temperature of −253 °C. It is practically impossible to insulate the tank well enough by passive means to prevent boil-off and a slow evaporation must be taken into account, unless active cooling is provided, a process that has its costs in terms of energy. Also the difficulties of filling safely the tank with such a liquid are clear. Anyway, BMW chose this way for the BMW Hydrogen 7 research car.

An alternative is storing hydrogen as a gas in pressurized tanks. Bottles able to keep a pressure of 350 or 700 bar are usually employed and even higher pressures are under study. The density of hydrogen at 800 bar is 36.6 kg/m^3, about half of its density in liquid form at atmospheric pressure. The energy needed to compress the hydrogen is not too large, but also not negligible, amounting to something like 2 % of the total energy content.

The safety problems linked with storing several kilograms of a highly flammable gas at such high pressures on board a vehicle are clear. Filling operations are difficult too, and time consuming, although faster than recharging the batteries of a battery electric vehicle. Further increases of storage pressure would produce an increase of the weight of the tank: an optimum between the decrease of the volume and the increase of the wall thickness with increasing pressure must be sought.

To increase safety, the pressurized hydrogen tanks are made in three layers: a polymeric, gas tight, inner one, a carbon fiber intermediate one able to withstand the internal pressure and an outer layer able to protect the inner ones against mechanical and corrosion damages. Several manufacturers such as GM, Honda or Nissan built experimental vehicles in which hydrogen is stored in this way.

The two techniques can be combined in cryo-compressed storage devices: hydrogen is stored at cryogenic temperatures, but when it boils off it is initially not vented and the pressure is allowed to rise up to about 350 bar, so that much less hydrogen is lost, in particular if in the meantime the vehicle is used and the fuel is consumed.

Other approaches have been followed: they can be subdivided into chemical and physical systems. In the most common chemical systems hydrogen is stored in metal hydrides, such as MgH_2, $NaAlH_4$, $LiAlH_4$, LiH, $LaNi_5H_6$, and $TiFeH_2$, with varying degrees of efficiency. Some of these hydrides are liquid at ambient temperature and pressure, while others are solid. Their energy density by volume is usually good, while their energy density by weight is usually worse than that of hydrocarbon fuels. The problem with this kind of storage is that energy is required both to store and to release the hydrogen from the hydrides. The weaker the bond of the hydrogen atoms within the compound the more energy is required in the first phase and the less in the

second, so that also here a compromise is required. The goal is a temperature lower than 100 °C for release and a pressure lower than 700 bar for recharge. Catalysts can help in these issues, but a satisfactory solution has not yet been found.

Hydrogen can be bound to form carbohydrates that can be stored in liquid or solid form. Glucose, cellulose, starch, have been tested. Also synthetic hydrocarbons can be used as hydrogen carriers, but the disadvantage is the need of a reformer on board to extract the hydrogen from the compound, that makes the powertrain complex and costly.

Ammonia is a hydrogen carrier that is produced in large quantities and can be burned in slightly modified gasoline automobile engines but at standard temperature and pressure is a toxic gas with quite a bad smell. Other chemicals that can be used as hydrogen carriers are amine borane complexes, formic acid, imidazolium ionic liquids, phosphonium borate carbonite substances, etc.

Apart from cryogenic and compressed gas storage, which can be dubbed as storage by physical means, other forms of physical storage of hydrogen exist. For instance, hydrogen can be stored in nanostructured carbon, like carbon nanotubes, although how much hydrogen can be stored in this way is still controversial. Other porous materials, like metal-organic frameworks, glass capillary arrays, glass microspheres, can store hydrogen, in particular at low temperatures.

The research is proceeding and new chemical and physical storage devices are constantly found, but they all are a long way from being practical, safe and cost effective energy storage devices. As it was said in the preface, the very wide variety of the proposed methods show that these technologies are still quite young and a long time may be required to establish standard methods and techniques.

The various devices are characterized by a performance index, namely the ratio between the mass of the contained hydrogen and the mass of the full tank (hydrogen plus container). The American Department Of Energy (DOE) has stated a goal of 0.065 for this performance index, i.e. for every kilogram of hydrogen a tank of 14 kg is required, but lower values are now considered as satisfactory, like the value 0.04 obtained with storage pressures of 450 bar. If all ancillary equipment, like pressure and temperature control devices, etc. is considered, even lower values can be achieved.

The ratio between the mass of the hydrogen and the volume of the tank is about 70,6 kg/m^3, roughly equal to the density of liquid hydrogen.

14.3.2.3 Utilization

As already stated, hydrogen is the cleanest fuel and can be used by burning it in a more or less conventional engine or by having it react with oxygen in a fuel cell. The first alternative is for sure the simplest one, since a conventional internal combustion engine can be easily converted to hydrogen usage, but is characterized by a low efficiency, since the chemical energy of the fuel must be first converted into thermal energy and then into mechanical energy and the efficiency of the latter transformation has the limitations stated by the second principle of thermodynamics.

In a fuel cell the same reaction goes on without liberating thermal energy (or at least too much thermal energy, since some fuel cells operate at high temperature, although lower than that characterizing combustion) and chemical energy is converted directly into electric energy. However, although there is no theoretical strict limitation to the efficiency of this process, the efficiency of a fuel cell is much lower than the theoretical 100 % maximum. Moreover, the electric energy must be furthermore converted into mechanical energy in an electric motor, and the efficiency of this latter transformation must be accounted for. The overall efficiency is between 20 and 50 %, depending on the type of fuel cell, motor and controller used.

As a conclusion, the problems with hydrogen vehicles provided with internal combustion engines are mostly related with the storage of the fuel and the refuelling techniques and facilities. Prototypes with satisfactory performance can be built and have actually been produced and even a small series production is within the possibilities for the near future, particularly if the vehicle has dual fuel capabilities, so that it can work on gasoline when no hydrogen supply is available. The problems with large scale production and cost containment are however still to be solved and above all it makes little sense to produce hydrogen as an energy medium to use in internal combustion vehicles with the present mix of primary energy sources, even in countries where the share of electric power generated by nuclear energy is large, like in France (75.2 %): It is much better to use fossil fuels for vehicles while using different sources for producing electricity.

14.4 Reduction of the Resistance to Motion

The most obvious way to reduce the energy consumption of a vehicle is to reduce the so-called road load, i.e. the total resistance to motion. Any improvement in this area is not only effective in reducing fuel consumption, but also in decreasing emissions, since the amount of pollutant and greenhouse gas emitted is proportional, everything else remaining equal, to the amount of fuel burned, or more in general, to the amount of energy spent.

What has been said above applies in general, but there are cases where this effect is particularly important: in case of battery electric vehicles, for instance, the reduction of the road load leads to an increase of range, which is the most critical issue for BEV or, if the range is kept constant, in a reduction of the mass of the batteries. The mass of the electric motors and, consequently, the total mass of strategic materials needed for building batteries and electric motors, are reduced too.

In most of the vehicles seen in the previous parts of this chapter (hydrogen vehicles, electric vehicles of all types, including those powered by fuel cells, etc.) the total amount of energy carried on board is quite critical, and so anything that can reduce the total road load increases their feasibility.

14.4.1 Aerodynamic Drag

Much has been done in recent years to reduce aerodynamic drag of vehicles, in particular as a result of the energy crisis of the 1970s. Unfortunately, further improvements are at the same time more difficult and less effective: more difficult because it is difficult to further improve the already streamlined shape of present cars, and less effective because while aerodynamic drag was a substantial fraction of the total road load when the average C_x of cars was 0.45–0.5, now that it approaches 0.25–0.3 it is much less important.

Moreover, aerodynamic drag is important only at constant high speed, in practice in motorway driving, and the mileage driven by vehicles in these condition is a small fraction of the total, in many cases averaging something like 7 or 8 %. In the most frequent driving conditions, namely urban and suburban driving, the importance of aerodynamic drag goes from nil to marginal. This is even more so because of the speed limits imposed by the law in most countries: in North America, for instance, where motorway driving is more important than in Europe, the low speed limits make aerodynamic drag of little consequence. Germany is the only European country in which there are motorways with no speed limitations, and in these driving conditions the reduction of aerodynamic drag can be an interesting energy conservation practice.

This does not mean that a good aerodynamic design will not be important in the future: car aerodynamics does not deal only with drag reduction. Aerodynamic design deals with comfort (mostly noise reduction), safety (improving handling and stability) and other issues, like avoiding the deposition of dirt on head lamps and windows. The point is that in most cases these requirements are conflicting, and what is done to improve handling may for instance cause an increase of drag or an improvement in noise may cause a decrease of handling characteristics. It is well known that aerodynamic negative lift, essential to improve the performance of sports and racing cars by increasing the forces the tires can transfer to the ground, causes a strong increase of drag.

Aerodynamics is also strictly related with style, and with the habitability of a vehicle. As a general conclusion, we can expect that in the future motor vehicles will be carefully studied from the aerodynamic viewpoint but, nevertheless, the reduction of aerodynamic drag will contribute only marginally to the issues studied in the present chapter.

14.4.2 Rolling Resistance

The reduction of rolling resistance is on the contrary one of the most important ways to achieve a reduction of fuel consumption. Rolling resistance is the most important form of resistance to motion at low speed, and thus its reduction is important in urban driving, the condition in which cars are mostly used. It has two aspects:

reduction of the weight of the vehicle (see next section) and improvement of the rolling characteristics of the tires.

The first substantial improvement in this sense took place in the 1960s with the introduction of radial tires, whose rolling resistance is about 20 % lower than that of cross ply tires. In Europe radial tires became eventually compulsory, mostly for this reason.

Rolling resistance is mainly due to energy dissipation in the tire, and thus can be lowered by decreasing the damping of the tire material; in the usual formulation of elastomers used in tires, natural rubber has a lower damping than synthetic rubber and damping increases with increasing amount of carbon black in the compound. But while lowering damping lowers the rolling resistance at low speed, it makes the tire more prone to vibrate, and vibration causes a sharp increase of energy dissipation at high speed. At a certain speed (the critical speed) this increase causes overheating of the tire and this must be avoided: it is thus impossible to decrease too much the damping of the rubber material, at least in tires meant to be used on fast vehicles.

In the 1970s low speed, low resistance tires were built for electric vehicles, with the goal of increasing their range. At the end of the 1990s a new approach was introduced: by substituting silica for carbon black it was possible to introduce a dependence of the damping on the frequency, yielding tires with superior performances, accompanied by a lower rolling resistance. These tires were first introduced by Michelin and dubbed as *green tires* , with a play on words: they were *green* in the sense they used less energy, so lowering their environmental impact, but owing to the lack of carbon black they could be built in any color and, in the initial intention of their manufacturer, they would have also been green in color. Market studies showed that customers would not like tires of colors making them look like toys, and so they were colored in black, and the term ‘green’ applied only in a figurative sense. Notice that the term ‘green tire’ is also used in a wider sense, for any tire allegedly more environmentally friendly than traditional ones, and these claims are sometimes little substantiated.

The tendency toward a reduction of rolling resistance will continue in the future, with the obvious caveat that a tire is a complex object and that any change in its structure, material, production technology, etc. will affect its performance as a whole, from the ability to produce forces to safety considerations, from rolling resistance to cost and duration. A tire must be a compromise among all these features, and it makes no sense to try to optimize a single feature neglecting the other ones. It seems that at least a partial substitution of silica for carbon black is effective and that future cars will have a lower rolling resistance than present ones.

14.4.3 Vehicle Mass

Reduction of the mass of a vehicle has a twofold positive effect on the reduction of fuel consumption: on one side it reduces rolling resistance, and on the other it reduces the energy needed to accelerate, together with the energy to be dissipated

in the brakes. The energy needed to accelerate can be reduced also by reducing the moment of inertia of the rotating parts, at equal mass. These effects are all particularly important in urban driving, and so reducing the vehicle mass plays an important role in the conditions that are statistically the most frequent.

In spite of these considerations the mass of cars has increased in the recent past and it is difficult to predict a decrease in the near future. This is a result of several mechanisms, partly linked with customer's requirements and partly with the regulations imposed on the car industry.

From experience in the aeronautic industry, it is well known that weight reduction is not a matter of cutting much weight in a few selected spots of the vehicle, a thing that is usually impossible, but to shave a few grams in a large number of places. In a similar way, an increase of weight is not usually the result of adding a few large masses, a thing that is easily controlled, but of adding in many places masses that, each one considered in itself, seem to be negligible.

The first of these requirements are those related to passive safety. Modern cars must pass a number of safety tests that require not only an accurate structural design, but also the introduction of safety related elements. Safety has costs, and the increase of the vehicle mass is one of them. Structurally, the requirements of absorbing crash energy and at same time of providing a rigid survival cell, providing rigid attachment points for safety belts, introducing elements like air bags, with all the related electronics and deployment systems, anti-intrusion beams and plates, fireproof elements, etc. cause an increase of the vehicle mass.

Three wheeled vehicles, that in most countries are not required to comply with the safety regulations that apply to cars but to the more relaxed rules that apply to motorcycles, can be much lighter. The same is true for those microcars or quadricycles that, owing to their mass and power lower than given limits stated by the law, are not required to comply with the automotive safety rules. No doubt they are much lighter, but they are also much less safe, by design.

Active safety has a lower impact on the vehicle mass, but all the devices like ABS, antispin, VDC, EPS and so on have their electronic control unit, actuators and other devices that add to the mass of the vehicle. Large windows to improve visibility are another weight increase factor.

The ever-increasing search for comfort implies the introduction of phono-absorbent materials, vibration insulators and vibration absorbers and improved internal finishing materials. Even electronic devices, sometimes with an utilitarian scope, others just entertainment gadgets, have their mass.

Many customers still like large cars, and in many countries, particularly in Europe, the average size of cars has not decreased in the past years. In North America, after a decrease in the 1970s, as a consequence of the energy crisis, the size of cars started to increase again mostly due to the success of SUVs and the continuing popularity of pick-ups. This trend is not likely to be reversed, except for unexpected events like a generalized increase of the cost of energy or the introduction of regulations penalizing large cars.

From what has been said, it is predictable that the trend toward larger vehicle masses is going to continue. The only factors that may fight against it are the

improved stress analysis techniques, that can contain the structural mass through a more optimized design, and the introduction of new materials. These two factors, and in particular the first one, are not new, and in the past allowed reduction of the increase of the mass of vehicles below what could have been if the traditional approach was used. Both will be dealt with in specific sections.

14.5 Innovative Engines

Many proposal have been put forward in the past to radically change the type of engine used on motor vehicles and in particular on cars. The proposed alternatives came from many sources, but most of them could be summarized in the following trends:

- Internal combustion engines:

– gas turbines
– rotary piston engines

- External combustion engines

– steam engines
– hot gas engines.

None of these proposals had any practical success for a number of reasons. For sure one of them is the fact that standard reciprocating engines benefitted from a long history of development and a huge cumulative investment in research. The issue of whether any of the solutions above (or one of the others that may be conceived) could be the most successful engine type if it had the same century long history of development and improvements is questionable, and after all it is also of little interest. In the actual world things went as they did, and the engines we now have are the result of this development. The only things we can document are the reasons that caused the failure of these attempts.

14.5.1 Internal Combustion Engines

Gas turbines were regarded in the 1950s as a natural candidate to substitute reciprocating engines in vehicles, like they did in aircraft and helicopters, owing to their higher specific power and absence of reciprocating parts, which results in a smoother running and, at least in part, higher reliability and longer lasting. Turbines, particularly small ones, are much faster than reciprocating engines (the turbine of the 1963 Chrysler Gas Turbine Car, Fig. 14.4a, had a top speed of 44,500 rpm), implying a more complicated transmission. Moreover, they were much more difficult to control, at least when these attempts were made (presently, owing to simple microprocessor-based

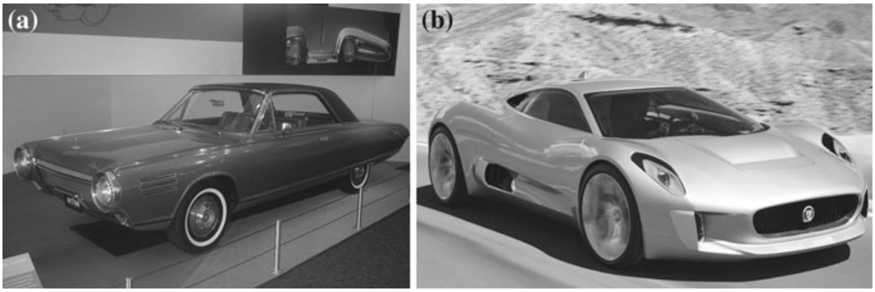

Fig. 14.4 **a** Chrysler turbine car of 1963. Five prototypes, plus 50 'production' vehicles were built. **b** Jaguar C-X75, hybrid car with 2 small gas turbines and 4 electric motors, built in 2011

controls, miniaturized gas turbines were successfully built), their fuel consumption is higher and their acceleration performance is poor. When the oil crisis broke out, their high fuel consumption stopped all attempts in this area and the many prototypes most manufacturers built in the 1960s were scrapped or ended in museums.

Now it is possible that gas turbines will make their comeback in the automotive industry for hybrid vehicles. In fact, modern ceramic materials and control technology allow miniaturization of this kind of engine, the possibility of coupling it directly with a very high speed generators allows us to dispense with a transmission (small turbojet and turboprop units used in model airplanes turn at 160,000 rpm or more, are low cost and fairly simple to use, although their life is too short for automotive application), there is no acceleration problem and above all their power density is high and their efficiency, up to 40 %, is better than that of diesel engines, and not much lower than that of fuel cells, while accepting a variety of fuels. Jaguar has built an interesting prototype of a turbine-powered hybrid car (Fig. 14.4b).

Rotary piston engines, like the Wankel engine, were introduced in the 1950s in the automotive field and had initially some success. Their main advantage is their compactness and smooth running, owing to the lack of reciprocating parts, but they have always been plagued by several problems, such as the wear of the rotor seals. Although from time to time some non automotive application resurfaces, after the oil crisis and the environmental laws their higher fuel consumption and the difficulty in complying with emissions regulations caused them to disappear from cars. In this case a comeback is unlikely.

14.5.2 External Combustion Engines

As described in Part I, steam engines were used to power road vehicles in the nineteenth century and at the beginning of the 20th, when their use was discontinued. The idea of returning to steam engines was revived during the oil crisis of the 1970s: the rationale was that while an external combustion engine can burn any kind of fuel

in its boiler, the control of emissions is easier in a continuous combustion than in an intermittent one. The usual advantage of not needing a clutch and gearbox with several transmission ratios and the drawback of requiring some time to build up steam pressure were not considered very important at that time, if compared with the issues of fuel consumption and emissions.

Several studies were done, but little reached the prototype stage. Sophisticated steam engines, with superheaters and other complex devices reached high values of efficiency, and as recently as 2006 an Automotive Engineering International Technical Award was given at the SAE World Congress in Detroit to Cyclone Technologies LLP, developer of steam engines for automotive applications. Their claim is that the engine has a 30 % efficiency.

With respect to better controlling emissions and using a variety of fuels, hot air engines have the same advantages as steam engines. They can be based on different thermodynamic cycles; the ones usually considered are closed cycles like the Stirling cycle (an engine that incorporated an innovative regenerator, then dubbed Economizer, patented in 1816 and built in 1818) or the Brayton cycle. Their advantage is high efficiency, and for this reason they were several times proposed for automotive applications but their low power density, both referred to the engine mass and volume, discouraged practical applications. Their use in extending the range of battery electric vehicles has however been attempted.

14.5.3 Improving the Standard Reciprocating Engine

While these innovative engines did not enter into production, and likely will not find applications at least in the near future, conventional reciprocating internal combustion engines, both of the spark ignition and diesel types, are continuously improving and future improvements are predictable. These improvements regard both performance, in terms of specific fuel consumption, specific power, emissions, and overall characteristics, like ease of maintenance and construction, and durability. In many cases these improvements were forced by the increasingly restrictive regulations regarding emissions, in other cases by market requirements and customers' expectations.

A powerful factor allowing these advancements was the introduction of microprocessor based controls for most of the engine functions, so that all working parameters could be kept under strict control and optimized. Other factors were the improvements of design techniques, made possible by Computer Aided Engineering, constructional techniques and new materials.

All these trends are still at work, and we can expect improvements in all these areas, so that even more strict requirements regarding emissions and fuel consumption will be met by the evolution of standard engines, without having to resort to more complex and costly solutions.